

CHARGED PARTICLE RADIATION DAMAGE IN SEMICONDUCTORS, VI:
THE ELECTRON ENERGY DEPENDENCE OF RADIATION DAMAGE IN SILICON SOLAR CELLS

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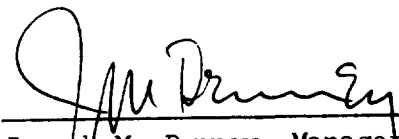
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ABSTRACT

A series of experiments utilizing electrons of energies from 0.4 to 22 Mev have been performed to measure the energy dependence of electron damage in p on n and n on p silicon solar cells. The results of the experiments indicate that although p on n solar cells closely follow the theoretically predicted energy dependence based on simple displacement theory, the n on p solar cells do not follow these predictions. The n on p cells are observed to exhibit a much greater damage rate dependence on electron energy, exhibiting approximately an order of magnitude increase in radiation sensitivity at 10 Mev over that calculated relative to 1 Mev. The reasons for this departure of the n on p cells from simple displacement theory are not completely understood at this time.

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I. INTRODUCTION

The effects of 1 Mev electrons on silicon solar cells have been studied extensively and are well established at this time¹. Because of the importance of electrons in the energy range from 1 to 10 Mev in the artificial radiation belt, an experiment was conducted for comparison with the theoretical energy dependence relationships based on classical Rutherford scattering theory. This experiment was conducted at the General Atomic linear electron accelerator facilities at San Diego. The purpose of this report is the presentation of electron damage data on silicon solar cells in the range from 0.4 to 22 Mev and the comparison of these data with theoretical damage rate predictions based on relativistic Rutherford scattering.

II. DESCRIPTION OF EXPERIMENT

The primary objective of this experiment was the comparison of the observed electron damage rate energy dependence for silicon solar cells with theoretical predictions based on simple displacement theory and relativistic Rutherford scattering. Therefore, primary emphasis was placed on obtaining accurate relative data as a function of electron energy on a small number of standard silicon solar cells. As a consequence of this technique (1) the data obtained on the cells tested can be extrapolated to other types of cells using the abundance of available 1 Mev electron damage data, and (2) the absolute accuracy of the integrated flux determinations is about a factor of two. Most important, however, the energy dependence is established independent of systematic errors using the accurately determined relative flux as a function of electron energy. The remainder of this section is devoted to a description of the experiment as performed.

Solar Cell Specimens

The solar cell specimens consisted of standard, commercially available Hoffman 1 ohm-cm p on n solar cells, Western Electric 1 ohm-cm n on p solar cells, and Hoffman 10 ohm-cm n on p solar cells. These cells were chosen primarily because of the vast amount of data existing on these types of cells,

their established quality and reproducibility, and their representation of "state-of-the-art" devices now available. These cells were preselected through short circuit current, diffusion length, and spectral response measurements and were as closely matched and representative of their type as possible.

Solar Cell Measurements

The measurements performed on the test solar cells at the irradiation site consisted of I-V characteristics under the STL light table using 2800°K unfiltered tungsten illumination at 110 mw/cm² nominal sunlight equivalent. These measurements were obtained before and after each irradiation for determination of degradation in short circuit current density. Diffusion length and spectral response measurements were obtained several days later at the STL facilities. All of these measurements are described in detail in Reference 1.

Dosimetry

The electron beam energy was measured by General Atomic personnel using a calibrated deflecting magnet. The deflecting magnet was calibrated through both range-energy experiments and activation threshold energies. The accelerator operates nominally in the 3 to 45 Mev region. Due to the large amount of time required to retune the machine for each individual energy, only four energies were obtained in the scheduled time. Taking into account the energy loss in the 0.010-inch titanium beam port window and air scattering between the beam port and the test specimens, the four incident electron energies on the test specimens were 2.7 Mev, 4.7 Mev, 9.8 Mev, and 22 Mev.

Due to the design principles of linear electron accelerators, the electron beam is a pulsed beam of variable pulse width and repetition rate. For this experiment, the operating parameters were 120 pulses per second at a pulse width of about four microseconds. Thus, the resulting duty cycle was 4.8×10^{-4} , and the peak electron beam current obtained was approximately two thousand times the average indicated electron beam current. The beam current was measured using several techniques. The first technique consisted of placing prebombarded solar cells in the electron beam and measuring the

resulting ionization current produced in the solar cell. The equipment used for this measurement consisted completely of STL instrumentation as used in previously reported experiments². In addition, an aluminum target one inch in diameter and six inches long was placed behind the test specimens. The current collected in the aluminum target was read in two different ways. First, the target current was read by General Atomic personnel using a properly terminated coaxial cable and an oscilloscope. The signal observed represented the peak pulse current. In order to determine average current from this signal, a calculation involving the duty cycle and observed beam pulse width was required. (Mr. H. Smith, General Atomic, reports that Faraday cup calibration of the aluminum target indicated an inaccuracy of less than 10 per cent with this technique.) Secondly, the aluminum target current was monitored directly with a current integrator which possesses an input pulse filter capable of accepting the stated beam characteristic frequencies. This target current was monitored in both rate and integral form. Though the use of an aluminum target as a beam current indicator is neither as accurate nor as flexible as the use of a Faraday cup, accuracies of within 25 per cent are readily obtainable. The primary inaccuracies of the aluminum target result from incident electrons that are scattered out of the target before they are brought to rest and measured.

Due to the geometries of the aluminum target, and the characteristics of electron scattering, the indicated beam currents are most likely less than the actual beam currents by not more than 30 per cent. Since General Atomic personnel were not able to monitor peak pulse current and repetition rate simultaneously, the integrated flux indicated on the STL current integrator is considered more accurate. For this reason, these values are used in the presentation of the data in a later section. The readings obtained using the STL current integrator were in agreement with the calculated beam current observed by General Atomic on their monitor scope to within 6 per cent. The resulting accuracy of the measured electron flux is, therefore, taken as better than -15 per cent to +30 per cent. The beam current readings obtained using the solar cells as ionization detectors were unusable for reasons which shall be discussed in a later section.

The flux distribution over the specimen test area was monitored using both cobalt glass and a special set of prebombarded cells arranged in a 16 cm^2 area. Since no quadripole focusing magnets were available at the particular beam port utilized here, no control over beam spot size was available other than beam scattering through the 0.010-inch titanium exit window and the five inches of air between the exit window and the test specimens. Consequently, it was characteristic of the accelerator to produce a decreasing spot size with increasing energy. The electron beam spot became too small at energies above 25 Mev to conduct any meaningful experiments without additional defocusing apparatus. At the energies utilized here, however, the intensity variation across the test specimen area of 4 cm^2 was less than ± 25 per cent. Because of the primary objective of the experiment, no effort was made to decrease the beam distribution variation over the area of interest at the sacrifice of obtaining additional energy dependence data.

Experimental Techniques

The specimens to be irradiated were mounted on an aluminum plate together with a monitor cell. The plate was mounted in a predetermined fixed position approximately five inches from the external beam port. A maximum of two $1 \text{ cm} \times 2 \text{ cm}$ solar cells was utilized in each separate irradiation in order to obtain as uniform a flux distribution as possible over the irradiation area. Each cell was subjected to two irradiations in succession with I-V characteristics measured at the conclusion of each irradiation. In this manner, two values of degraded short circuit current were obtained. Due to the careful pre-selection and calibration of the test specimens, only two points were required to obtain accurately the degradation rate and damage coefficient.

The one-inch diameter aluminum target used to measure beam flux was placed directly behind the test specimens and the plate. The test specimens and the plate were sufficiently thin that negligible error in indicated target current resulted with this geometry. Both p on n and n on p specimens were placed in identical positions; hence, any nonuniformity of flux distribution across the area would be maintained as a systematic error and preserve the observed relative relationships between n on p and p on n cells.

In order to compare the data obtained at electron energies from 2.7 Mev to 22 Mev with lower energy data, a similar series of experiments were run on the same lot of cells using the STL Van de Graaff at energies of 0.4, 0.6, 0.8, and 1.0 Mev. The experimental techniques utilized to obtain these lower energy data points are identical to those described in a previous report on the effects of 1 Mev bombardment on silicon solar cells¹.

III. EXPERIMENTAL RESULTS

The purpose of this section is the presentation of experimental results obtained for electron energies up to 1 Mev utilizing the STL electron Van de Graaff and from 2.7 to 22 Mev utilizing the General Atomic linear electron accelerator. The data consist of short circuit current degradation and spectral response degradation.

The observed degradation in I-V characteristics as a function of integrated flux for the specimens utilized in this experiment is consistent with all previously reported data in their response to charged particle radiation. Figures 1 through 8 depict degradation in observed short circuit current as a function of integrated flux. Shown in each of these figures is a $6\frac{1}{4}$ ma/cm² per decade slope of the type utilized in all previously reported data for this type of illumination. It is of interest to note that in almost every instance the observed data are in complete agreement with the standard slope as shown. The $\bar{\Phi}_c$ values to be discussed later were obtained from these curves by observing the fluxes required to produce a short circuit current density of 19 ma/cm² in each instance. The $\bar{\Phi}_c$ value utilized in each case represents the average of the two specimens of any given type irradiated at that energy. Figures 9 through 11 depict typical before and after spectral response characteristics measured at STL following the irradiations for each type of solar cell. The characteristic loss of long wavelength response is evident and no further comment is required here.

In order to compare the experimentally observed energy dependence with the theoretical energy dependence based on classical Rutherford scattering relationships, a plot of reciprocal $\bar{\Phi}_c$ versus incident electron energy was

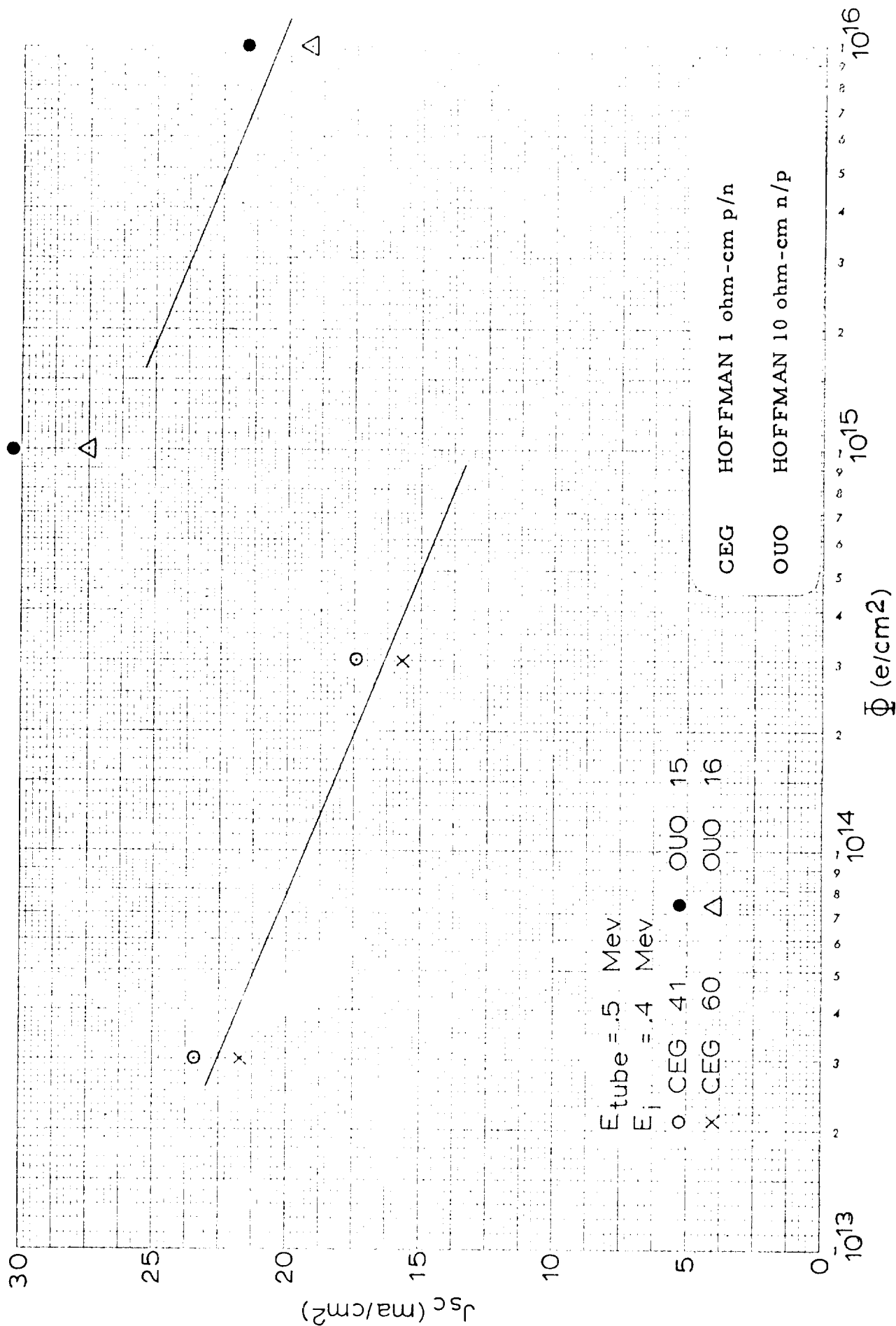


Figure 1- Solar Cell Short-Circuit Current Degradation under 0.4 Mev Electron Bombardment

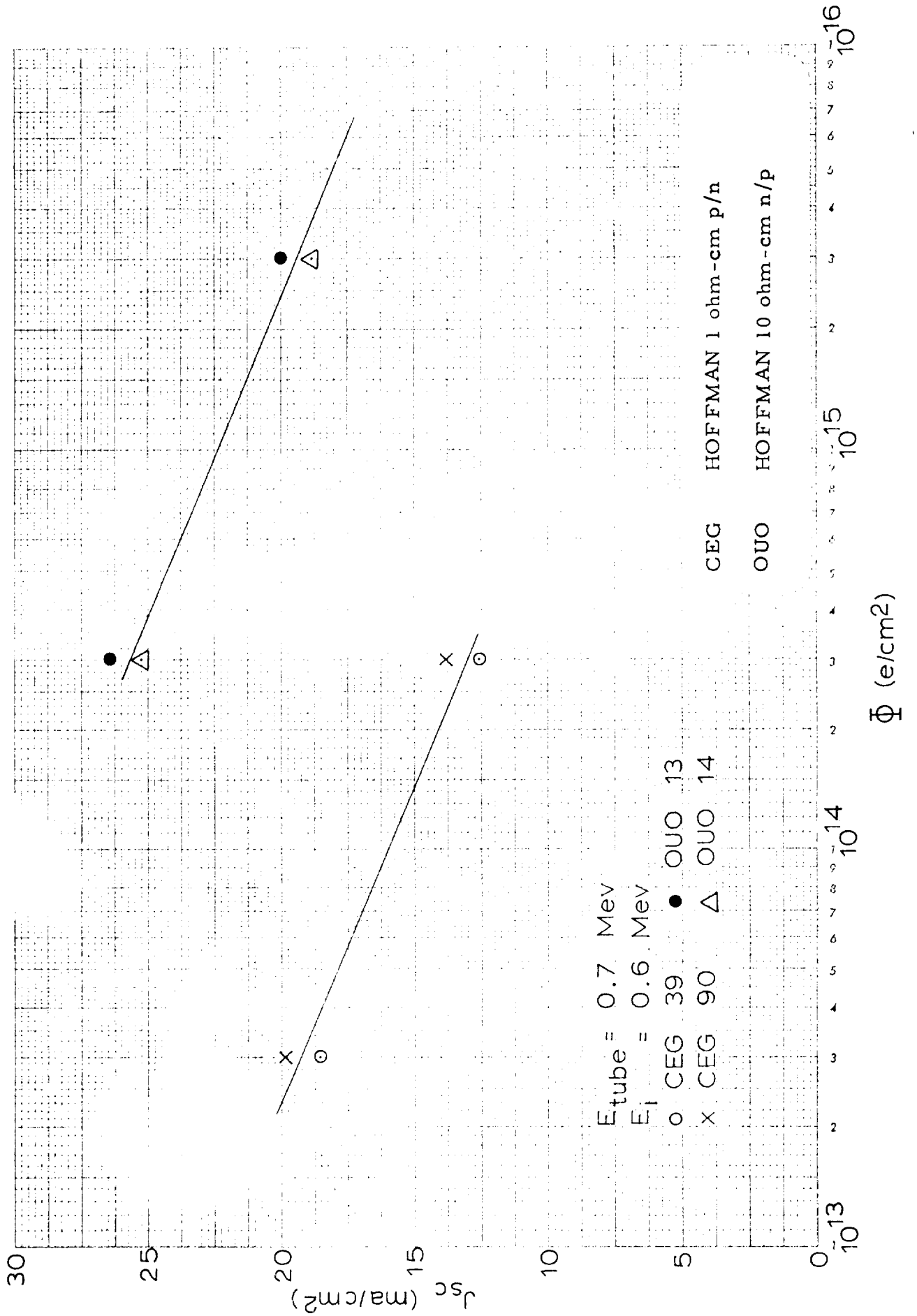


Figure 2. Solar Cell Short Circuit Current Degradation Under 0.6 Mev Electron Bombardment

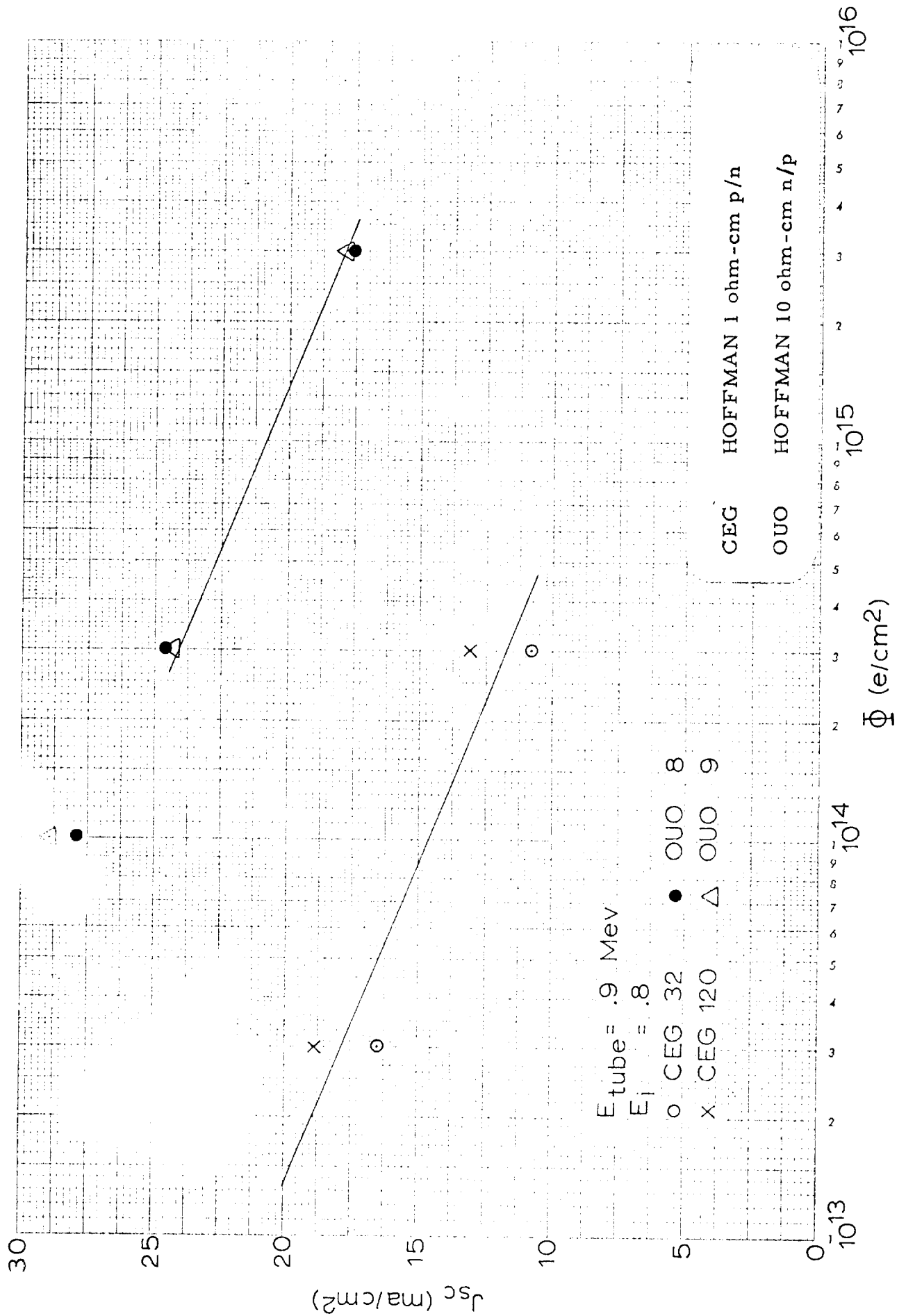


Figure 3. Solar Cell Short Circuit Current Degradation
Under 0.8 Mev Electron Bombardment

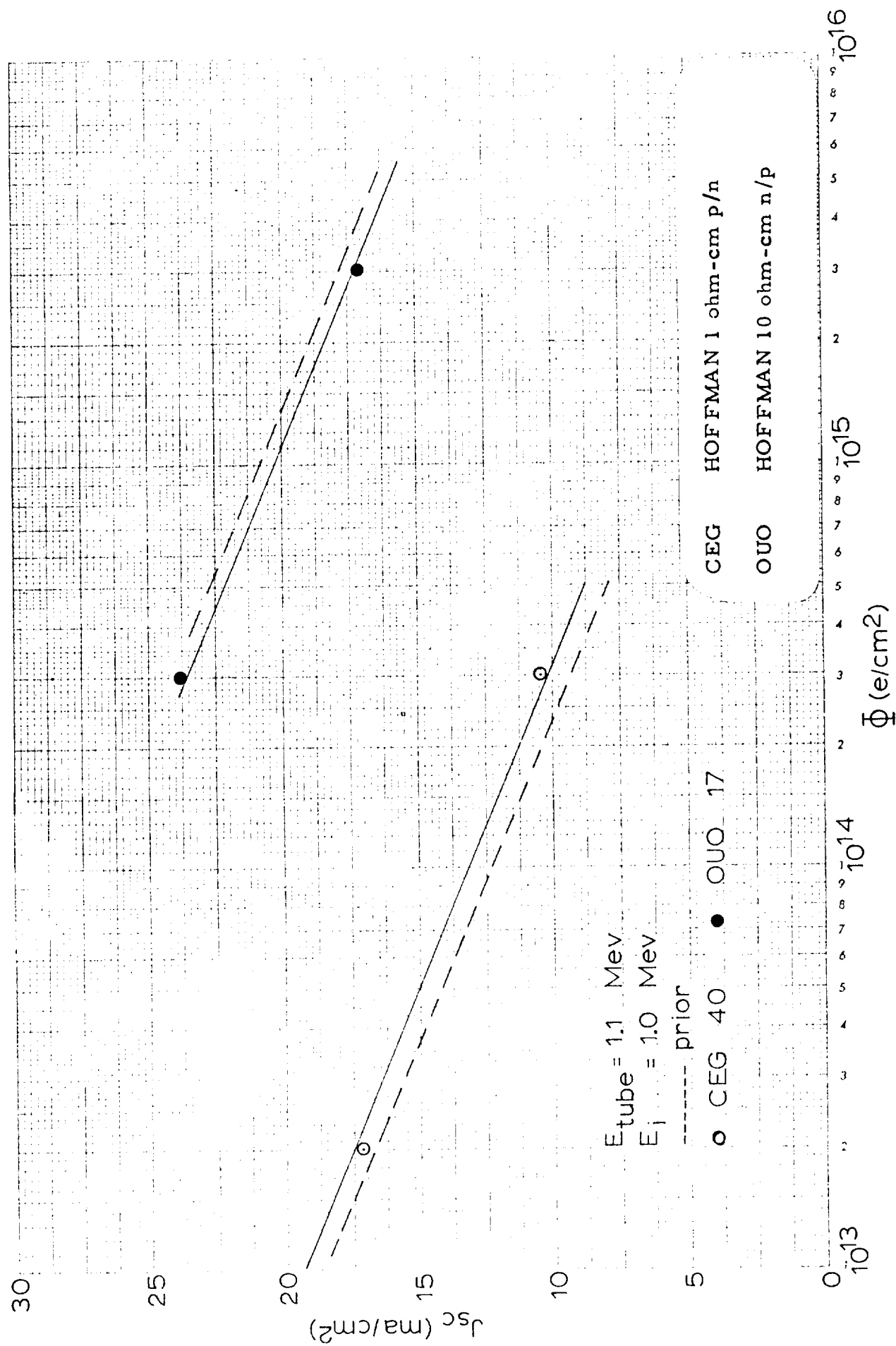


Figure 4. Solar Cell Short Circuit Current Degradation
Under 1.0 Mev Electron Bombardment

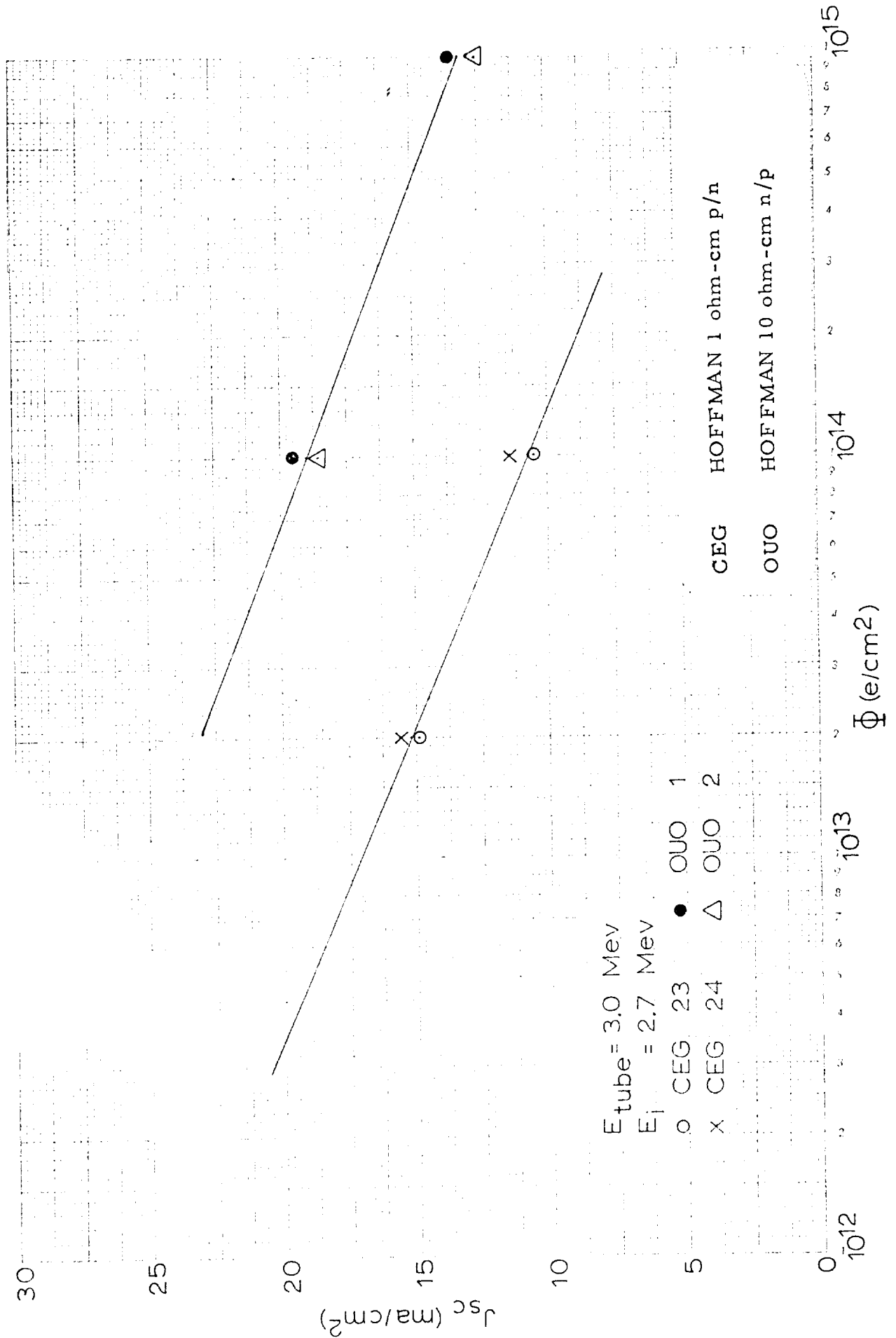


Figure 5. Solar Cell Short Circuit Current Degradation Under 2.7 Mev Electron Bombardment

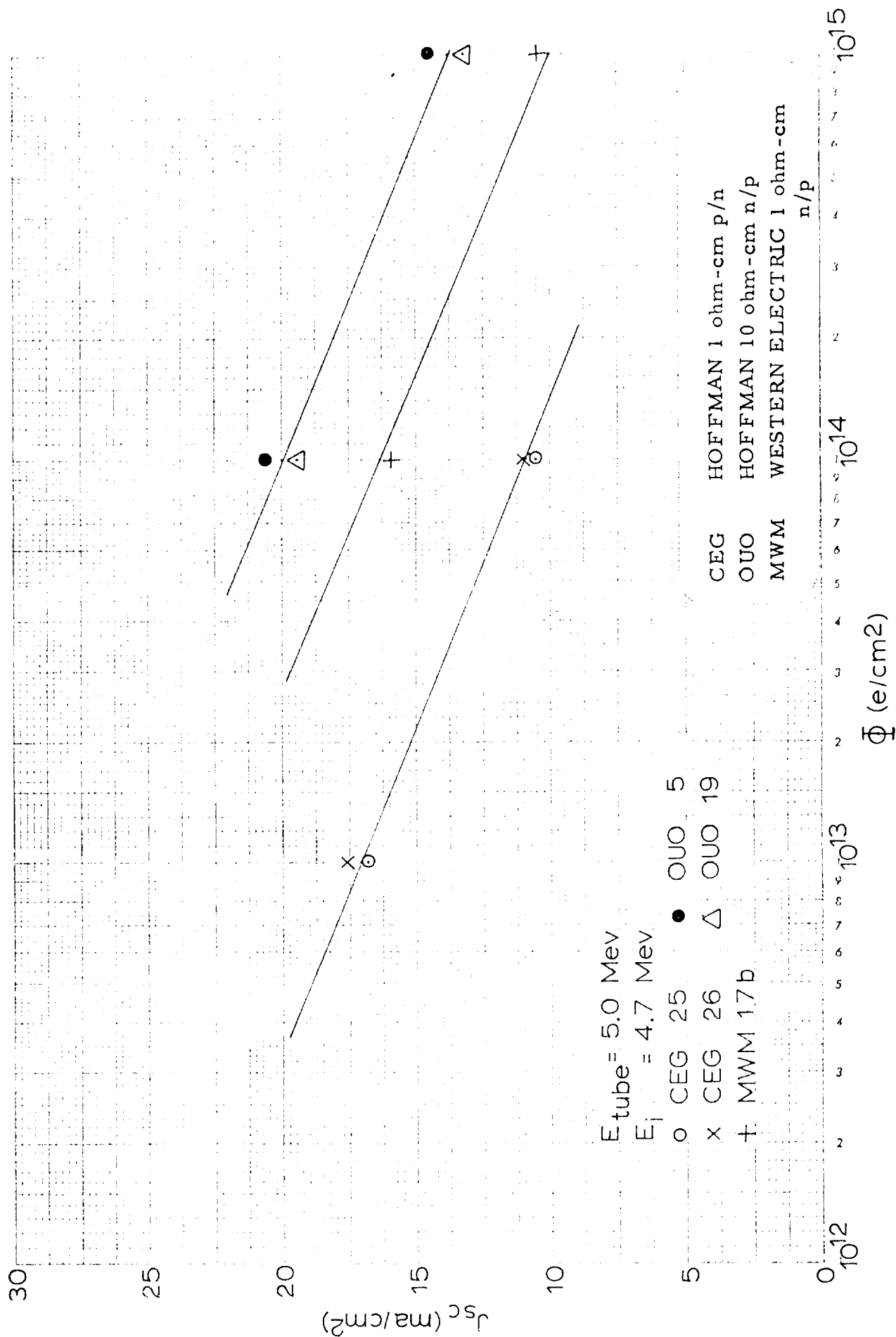


Figure 6. Solar Cell Short Circuit Current Degradation Under 4.7 Mev Electron Bombardment

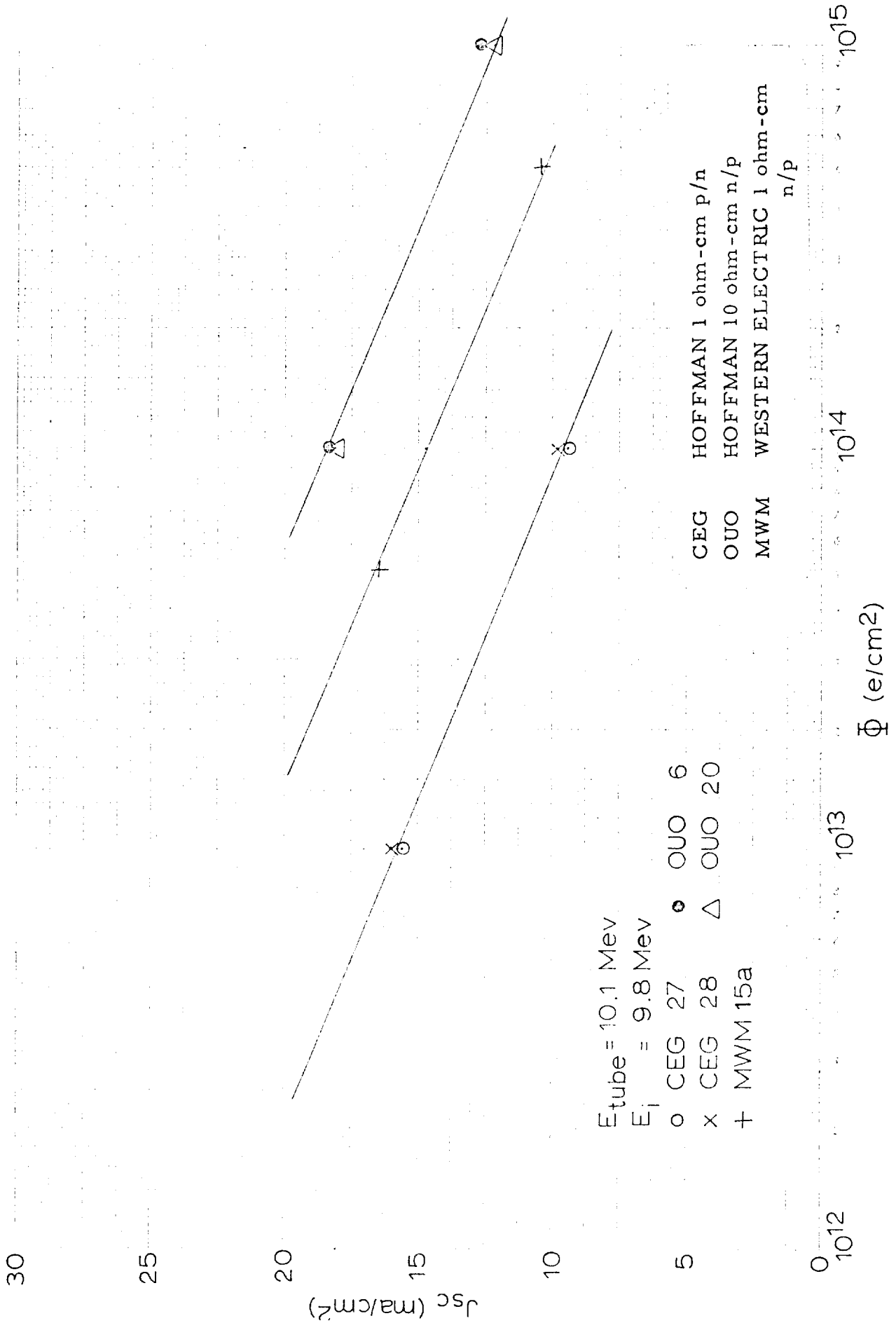


Figure 7. Solar Cell Short Circuit Current Degradation.
 Under 0.8 Mev Electron Bombardment.

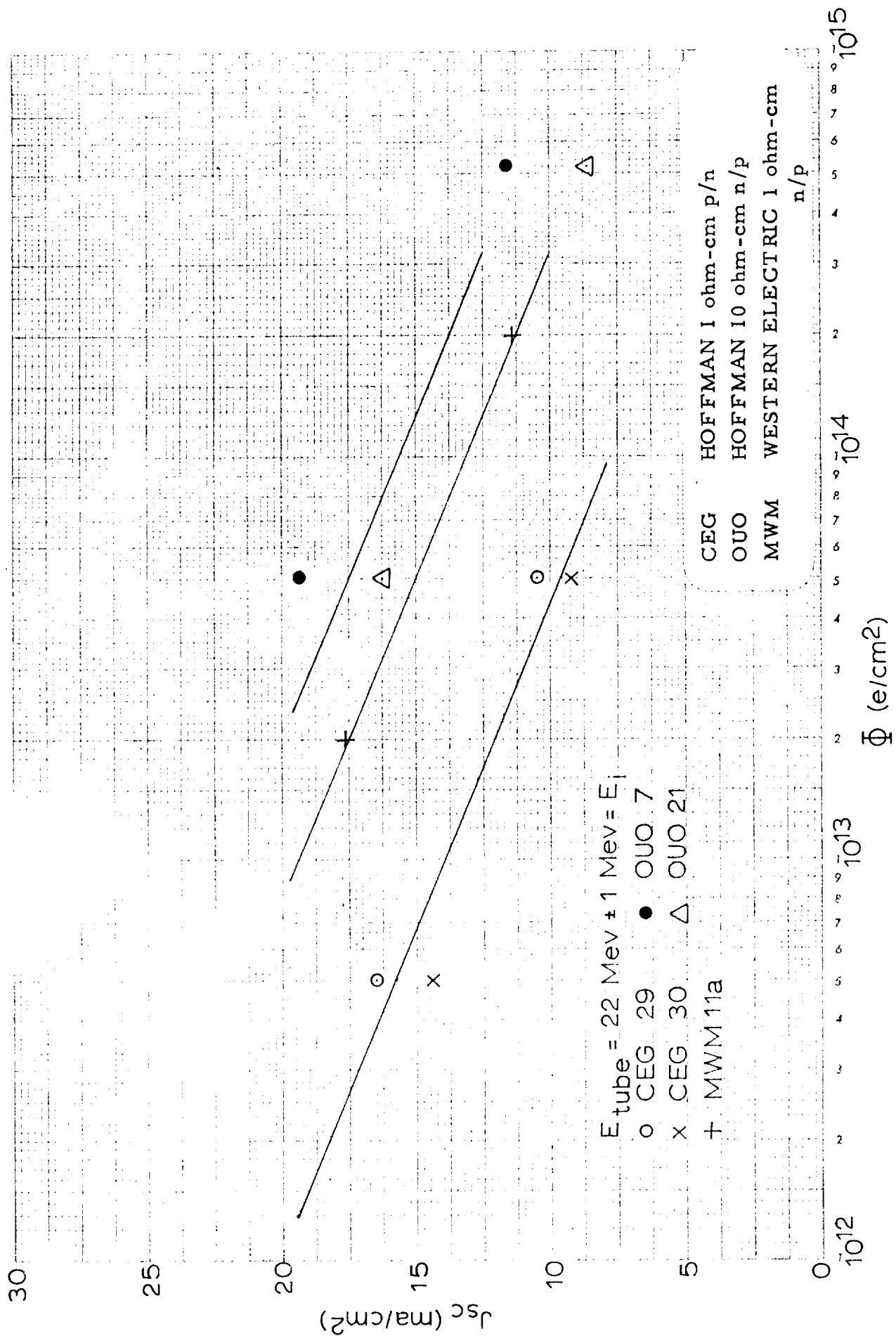


Figure 8. Solar Cell Short Circuit Current Degradation Under 22 Mev Electron Bombardment

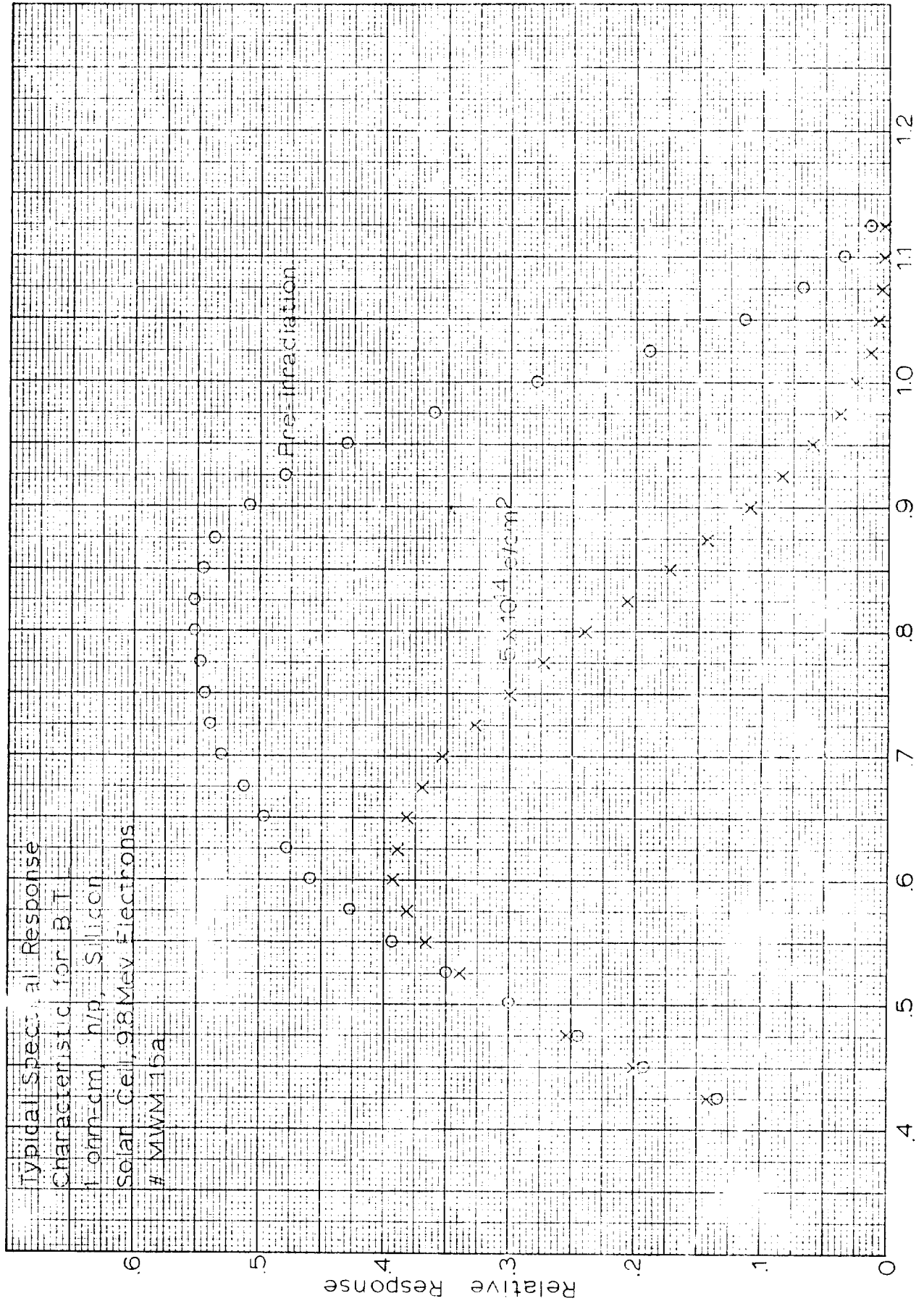


Figure 9. Typical Spectral Response Characteristic for BTL
n/p Silicon Solar Cell, 9.8 Mev Electrons

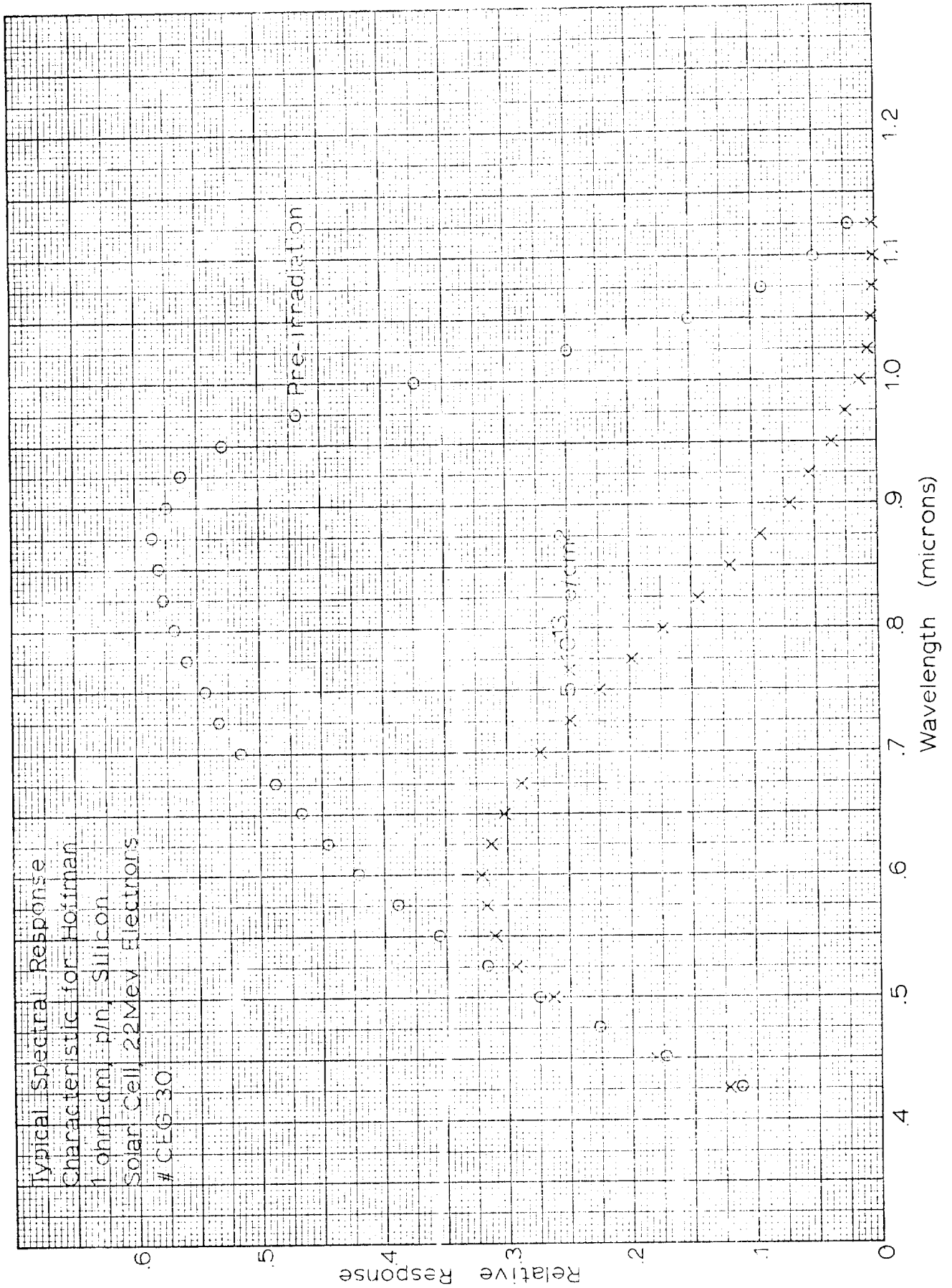


Figure 10. Typical Spectral Response Characteristic for Hoffman p/n Silicon Solar Cell 22 Mev Electrons

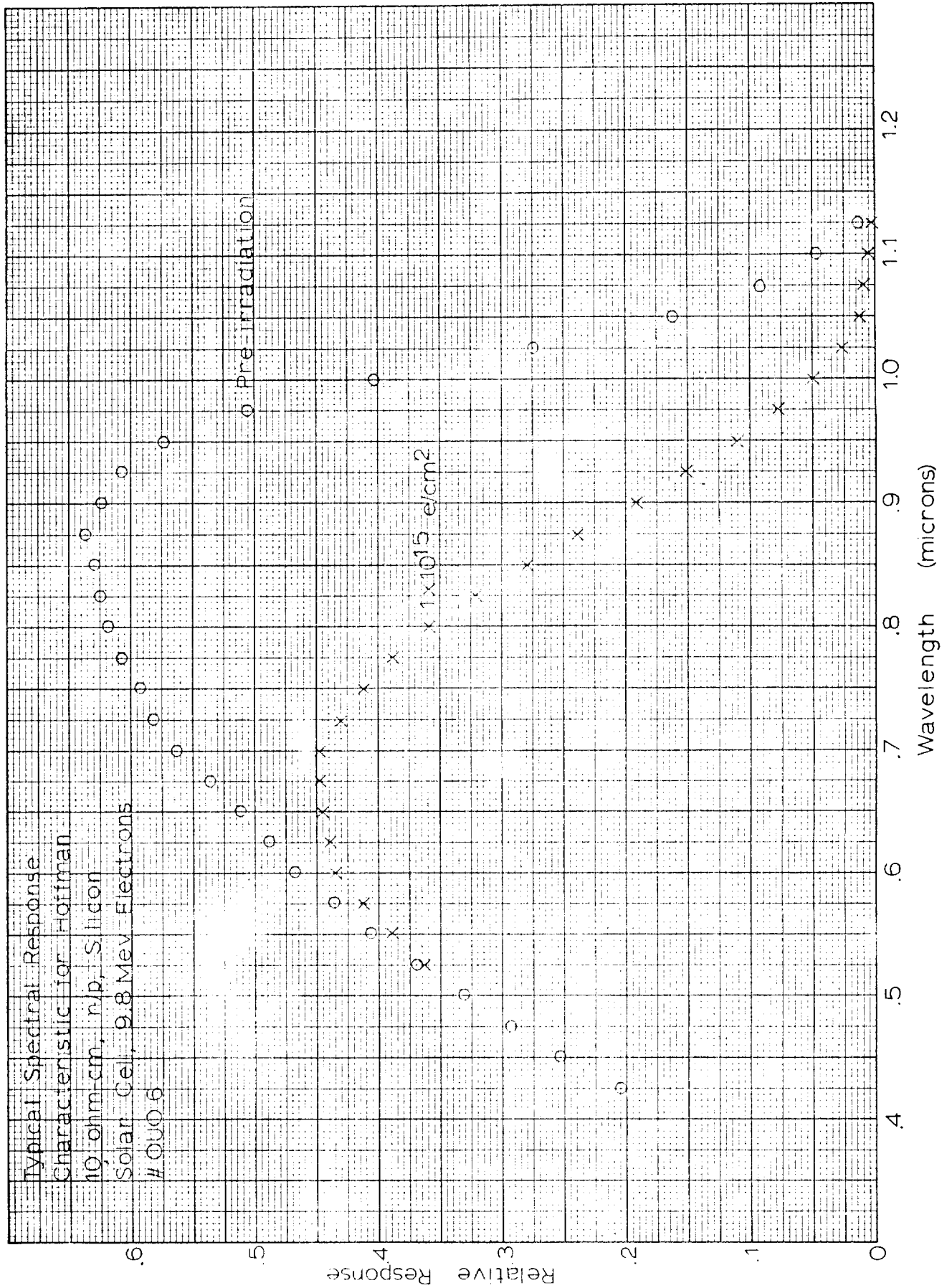


Figure 11. Typical Spectral Response Characteristic for Hoffman n/p Silicon Solar Cell 9.8 Mev Electrons

prepared. The choice of reciprocal Φ_c as the interesting experimental parameter results from the fact that the theoretical energy dependence is based on the amount of damage introduced per unit incident particle per unit area. The choice of logarithmic scales is for convenience in presenting and examining the data. The p on n and n on p cells are plotted separately in Figures 12 and 13, since their response to electron bombardment is far different. The theoretical energy dependence curve is readily obtainable by performing the calculations presented by Seitz and Koehler³. A plot of the theoretical energy dependence based on the referenced equations is shown in Figure 14. This relationship, normalized to 1.0 Mev, is shown in Figures 12 and 13 for comparison with the experimental data. The 22 Mev data are not shown in the experimental plots of Φ_c^{-1} versus energy since analysis of the raw data and examination of the cobalt glass distribution pattern indicate that the uncertainties are sufficiently large (due to the very small beam spot size) to render the 22 Mev data questionable.

Examination of Figure 12 for the p on n solar cell energy dependence indicates agreement with the simple theory within the experimental accuracies for energies above 1 Mev. The disagreement at energies below 1 Mev is thought to be associated with the use of a step function primary displacement cross section, wherein zero probability of producing a displacement occurs at energies below the displacement energy and unity probability of producing a displacement occurs at energies above the displacement energy. Further, the energy required to be imparted to a silicon atom for displacement, i.e., 12 electron volts, may be too small for these experimental situations. These conclusions, however, do not apply to the higher electron energies where the incident electron energy is far in excess of the energy required to produce a displaced silicon atom. The results of the experiment, therefore, appear to indicate that for p on n cells, or n-type silicon in general, the energy dependence of the electron damage rates appears to be consistent with the theoretical simple displacement theory.

Figure 13 is an identical type of plot of reciprocal Φ_c versus energy as previously discussed except only n on p cells are shown. Included are both 1 ohm-cm and 10 ohm-cm p-type silicon. In contrast to the previous example of

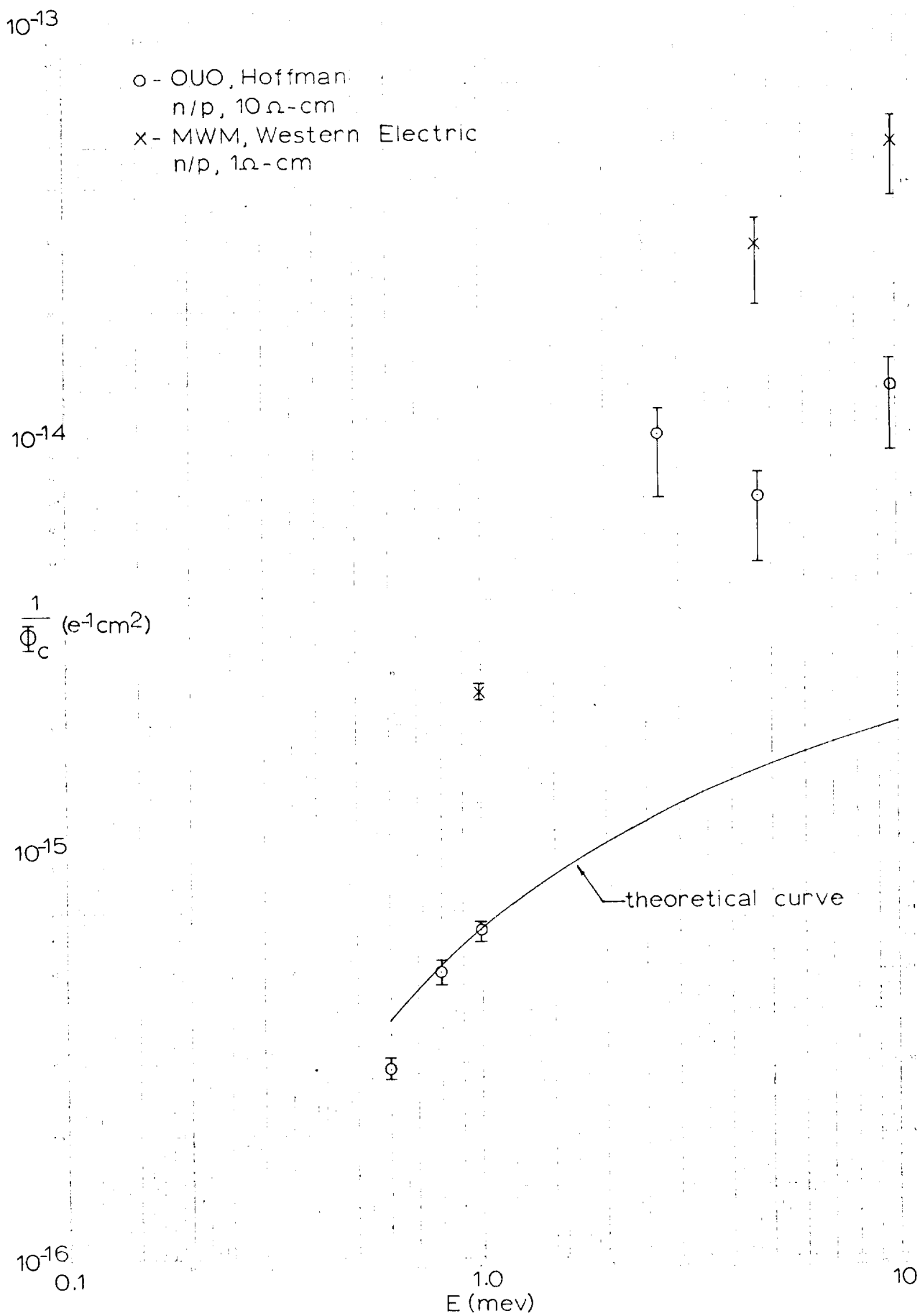


Figure 12. Energy Dependence of Electron Radiation Damage on n/p Silicon Solar Cells

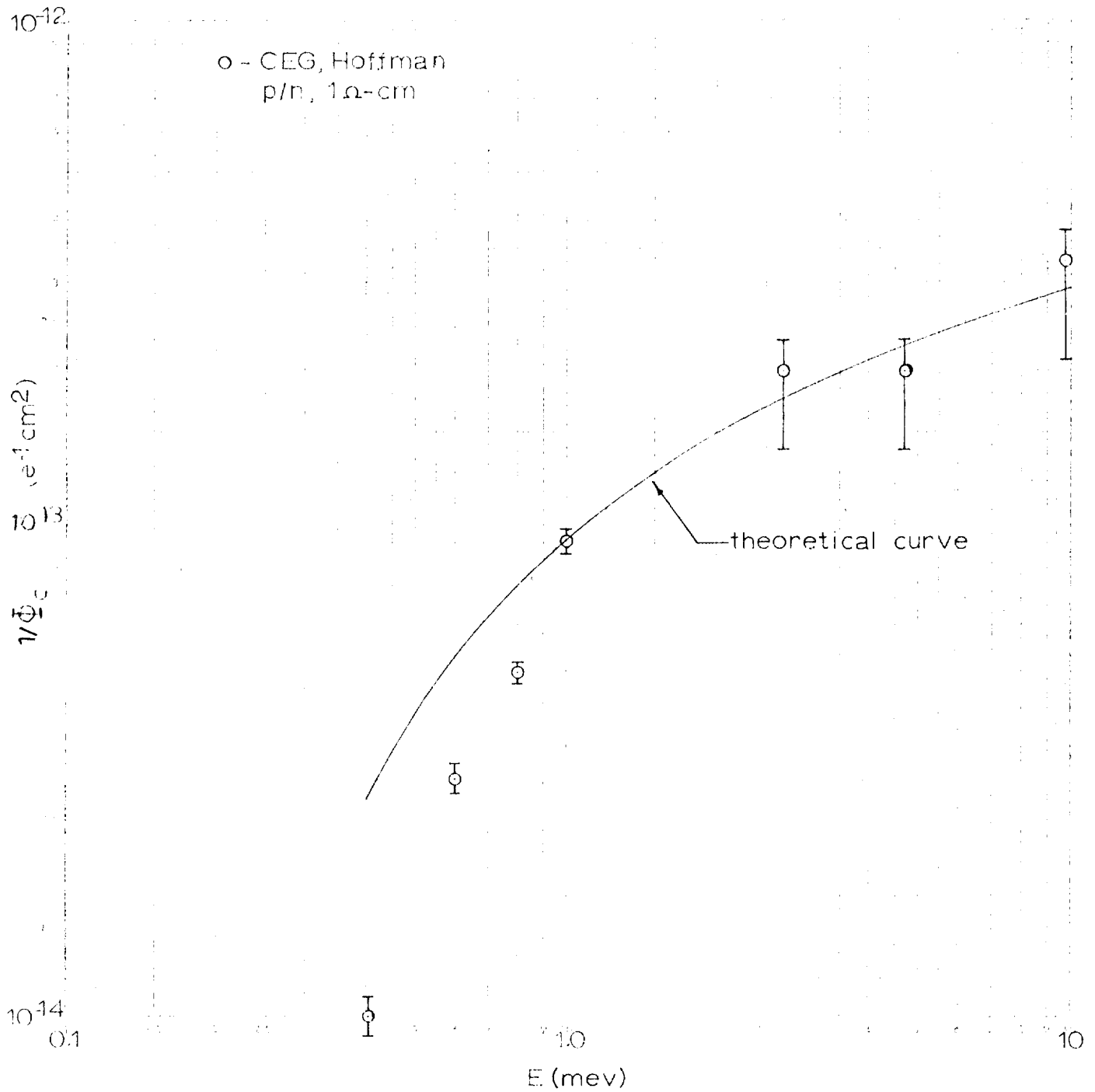


Figure 13. Energy Dependence of Electron Radiation Damage on p/n Silicon Solar Cells

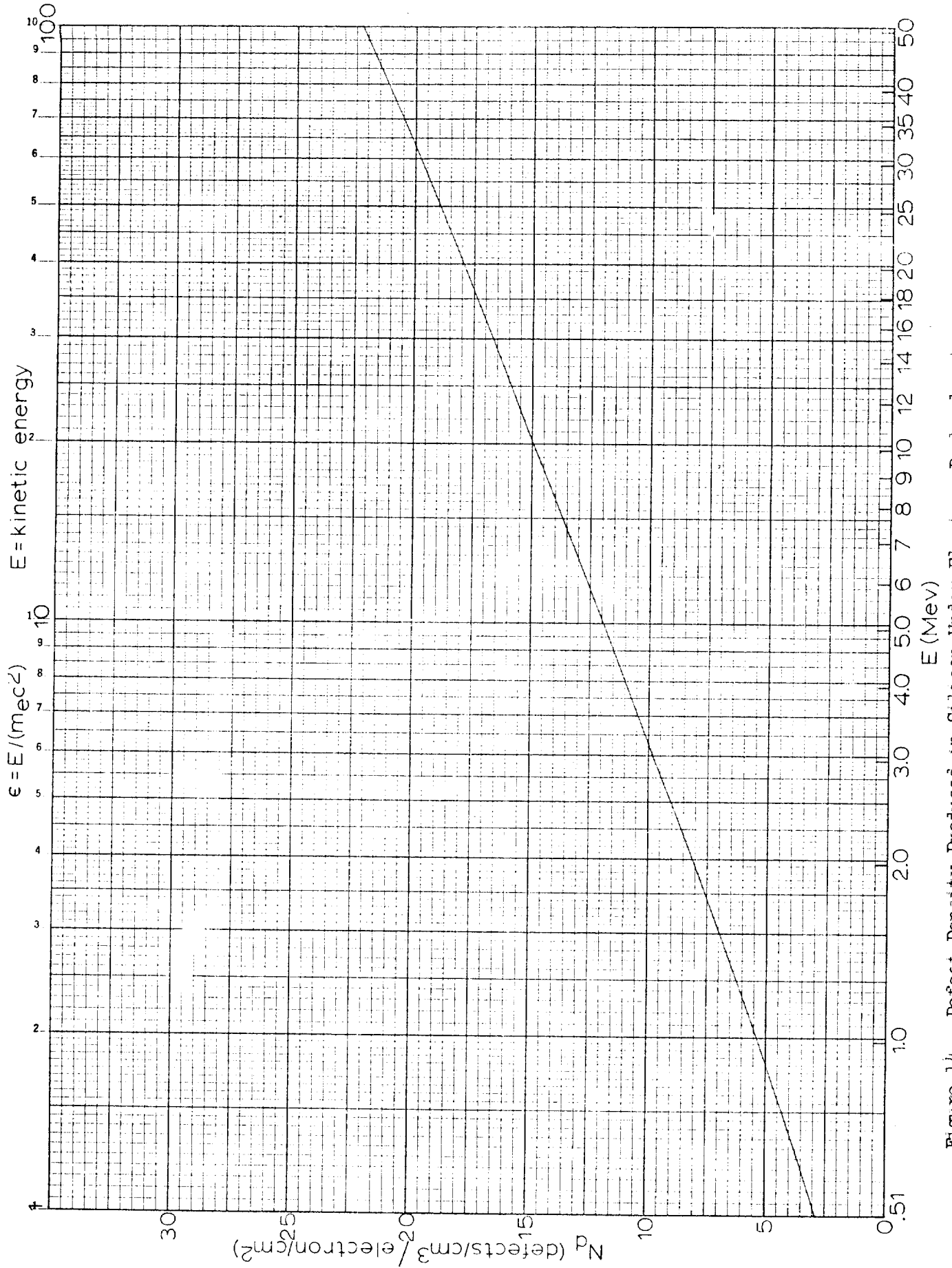


Figure 14. Defect Density Produced in Silicon Under Electron Bombardment
Based on Relativistic Rutherford Scattering Laws

p on n cells, these data indicate that n on p solar cells do not exhibit the same energy dependence as predicted from the simple displacement theory. It is observed that the data at 10 Mev appear to indicate a sensitivity to electron bombardment in excess of that predicted by about an order of magnitude for both 1 ohm-cm and 10 ohm-cm p-type silicon. No ready explanation can be offered for this observed behavior. However, due to the previously discussed experimental accuracies involved in the determination of the integrated electron flux and due to the observed agreement in the case of the p on n solar cells, it must be concluded that most of this observed difference is real.

An additional result obtained in this experiment, though not directly related to the energy dependence of electron damage in silicon solar cells, is the applicability of the use of prebombarded solar cells as radiation intensity monitors for this type of experiment. In the preparation for this experiment, a series of n on p solar cells were heavily prebombarded with 1 Mev electrons to diffusion lengths of five microns. It was planned to use the cells as both electron intensity monitors by placing one cell on each experimental plate and as intensity distribution monitors by placing nine of these cells in a 16 cm^2 area on one plate. Before the initiation of the actual solar cell irradiations, a series of measurements were performed comparing the electron flux and distribution obtained using solar cell monitors with the intensity and distribution measurements obtained utilizing aluminum targets and cobalt glass. The results of these comparisons were in disagreement by about an order of magnitude. The accelerator operating characteristics, as previously discussed, were 120 pulses per second at a pulse width of four microseconds. The corresponding average beam current was approximately 1.7 microamps and the peak beam current during the four microsecond pulse was approximately four milliamps. Using the standard handbook values of dE/dx for electrons in silicon, 3.6 electron volts to produce a hole-electron pair, and the five micron diffusion length previously determined at STL, a peak current generated during the four microsecond pulse in the solar cell is calculated to be of the order of three amps. This peak current is in excess of the capability of typical pn junctions of the geometry commonly utilized for solar cells. These conclusions are supported by the fact that the observed beam currents indicated by the monitor cells were an order of magnitude

below observed beam currents obtained by other techniques. Since the accelerator's operating characteristics could not be altered sufficiently to allow lower peak currents and still perform meaningful experiments, the use of solar cell monitors was discontinued. As was shown here, care must be exercised in using this technique under pulsed beam conditions to insure that during the short period of time in which high currents are delivered, the solar cell has not operated in a saturated condition. This problem is far more severe with pulsed electron accelerators than with pulsed proton machines such as cyclotrons because of the much lower ratio of displacement damage produced to ionization current produced in a monitor cell.

IV. CONCLUSIONS

The primary objective of this experiment was to determine whether p on n and n on p silicon solar cells exhibited an experimental dependence on electron energy as predicted using the simple displacement theory. The energy range covered in this experiment extended from 0.4 to 22 Mev. Although no attempt was made to obtain extremely accurate dosimetry measurements, the results clearly indicate a difference in response between p on n cells and n on p cells. It is observed that within the accuracy limits of the experiment the p on n cells follow the predictions of energy dependence based on simple displacement theory. It is also observed, however, that n on p cells do not follow the theoretical relationships but rather exhibit an order of magnitude higher increase in radiation sensitivity with increasing electron energy. Since the observed departure of the experimentally observed electron energy dependence of the n on p cells is much greater than the inaccuracies of the experimental determinations of the integrated flux, it must be concluded that the observed effect is real.

The importance of this effect lies in its integration with the fission beta energy spectrum for the electrons in the artificial radiation belt. The result of the folding of this n on p solar cell energy dependence with the fission beta spectrum is an increase in the predicted damage rate of about a factor of three over that predicted on the basis of the damage energy dependence of p on n solar cells. Clearly, these preliminary results suggest that a more thorough examination of this phenomenon be conducted for both types of cells as soon as possible in order to amplify these results.

The reasons for the "steep" electron energy dependence exhibited by n on p silicon solar cells, or p-type silicon in general, are not understood at this time. This effect, however, is not the first time p-type silicon has been observed to respond in a peculiar manner to charged particle radiation. Other typical examples of phenomena which are also not well understood at this time concerning p-type silicon are the effect of resistivity in the 1 ohm-cm to 10 ohm-cm region on the measured degradation rates and the observed differences in response of p-type silicon relative to n-type silicon when considering protons and electrons in general. In this latter case, p-type silicon is observed to be only a factor of three more radiation resistant than n-type silicon under proton bombardment at any energy while the ratio of radiation resistance of p-type silicon to n-type silicon under electron bombardment has been observed to vary from 10 to 150 depending upon the electron energy and the resistivity of the p-type silicon. It is evident that the fundamental physics of the interactions of the defects produced by charged particle radiation in p-type silicon are complex inasmuch as the initial defects produced in either type of silicon must be identical in characteristics since both p-type and n-type silicon are in effect extremely pure silicon in which the initial interaction is the displacement of a silicon atom from its lattice site. The observed peculiar responses of p-type silicon must, therefore, be associated with complex interactions of these defects with other impurities or crystalline imperfections and the relative importance of divacancies in n and p-type silicon. Further, it is not clear why the secondary interactions should depend so strongly upon the type and energy of the incident particle producing the primary displacements. Considerable basic research will be required before these observed phenomena can be explained.

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